# *U.S. PATENT APPLICATION*

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*Invention:*    DISPERSION MANAGEMENT SYSTEM FOR SOLITON OPTICAL
TRANSMISSION SYSTEM

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# *SPECIFICATION*

## Optical communications

This invention relates to optical communications and, in particular, to optical communications systems in which information is transmitted by soliton or soliton-like pulses.

5      Laboratory demonstrations have recently been reported of soliton transmission in systems where the dispersion was not uniformly anomalous along the fibre, instead being periodically compensated by fibre of opposite (normal) sign dispersion. In this manner transmission was achieved at 20Gb/s over 9000km in a recirculating loop, and 8100km in a straight line experiment. These figures are substantially in excess of what has previously

10   been achieved without the use of soliton control techniques such as sliding filters and synchronous modulators. While it is thus clear that there are significant benefits to be gained from adopting dispersion management in soliton systems, to date there has been little conceptual explanation of the mechanisms behind this improvement.

The correct selection of dispersion is a critical issue in the design of amplified long

15   haul optical communication systems. In the case of soliton formatted data, it is dictated by compromise between the desire to minimise timing jitter problems (implying low dispersion), and the need to maintain adequate energy per bit for successful detection. As the energy needed to form a soliton in a uniform fibre is proportional to the dispersion, the latter constraint places a lower limit on the permitted dispersion. Dispersion management

20   is a technique in the context of non-return-to-zero (NRZ) formatted data in which fibres of opposite sign dispersions are concatenated together. This produces a high local dispersion at any given point,, and yet a low path-average dispersion. We have found that, by adopting a suitable dispersion management scheme for soliton or soliton-like transmission, it is possible to increase the soliton energy substantially compared with the equivalent

25   uniform fibre with equal path-average dispersion.

According to the present invention there is provided a dispersion management system for soliton or soliton-like transmission in which the duration of a dispersion compensation phase is short in comparison with the propagation interval in the remainder of the system.

30      Preferably the system excludes arrangements in which the dispersion map of one fibre is substantially closer to zero than that of its complementary fibre.

The invention will be particularly described with reference to the accompanying drawings in which:

Figure 1 is a dispersion compensation map;

Figure 2 shows the pulse profile at the beginning of each unit cell in a dispersion managed system. The dispersion map comprises alternating 100km fibres with dispersions of -3ps$^2$/km and +2.8ps$^2$/km;

Figure 3 shows the evolution of a over one period of the dispersion compensation cycle

Figure 4 shows the energy required to launch a 20ps FWHM soliton in dispersion managed system with alternating 100km length fibres chosen such that the path-average dispersion remains at -0.1ps$^2$/km, and

Figure 5 is an outline diagram of a dispersion management system in accordance with one aspect of the invention

Our work is based upon numerical integration of the Nonlinear Schrödinger Equation (NLS), using the dispersion map shown in Figure 1. The arrangement of a typical system is shown in Figure 5 and comprises a transmitter T and Receiver R lined by a length L of fibre. This fibre is divided into elements l comprising separate sections of fibre N with normal dispersion and fibre A with anomalous dispersion. In a specific embodiment these are of equal length, although the unit cell is defined to start and end at the mid point of one of the fibres. In the specific examples presented, each of the fibres will be 100km long, and the path average dispersion -0.1ps$^2$/km. The nonlinear coefficient was taken to be 2.65rad/W/km. To simplify the problem we have chosen to neglect loss and high order dispersion throughout.

We have confirmed the existence of quasi-stable soliton or solitary wave solutions to this dispersion map. Figures 2 and 3 show the observed behaviour when the dispersion values alternated between -3.0ps$^2$/km and +2.8pS$^2$/km, and a 20ps FWHM Gaussian pulse of peak power 650$\mu$W was launched into the fibre. Figure 2 shows the intensity profiles at the start of each unit cell; it can be seen that the pulse profile at these points remains unchanged over successive cycles of the dispersion map. The evolution within one unit cell is shown in Figure 3, the pulse alternately compressing and dispersing as the sign of the dispersion is switched. The power spectrum remains essentially unchanged within the unit

cell.

There are three constraints which must be satisfied to obtain stable solutions to the periodic dispersion map. Firstly, the path average dispersion must be anomalous, in order that the Kerr induced spectral broadening can be compensated. Secondly, the period of the

5    dispersion compensation cycle must be short compared to the nonlinear length of the system. For a 1000Km fibre, the dispersion compensation length is preferably 100Km or less. Finally, dispersion maps in which one of the fibres is much closer to zero dispersion than the other should be avoided. as otherwise energy is rapidly coupled out of the pulse into dispersive waves.

10    The advantages conferred by a dispersion management scheme on soliton communications stems from the fact that more energy is required to launch a stable pulse than in the equivalent uniform system with equal path average dispersion. This is demonstrated in Figure 4, which plots the pulse energy of the stable solution as a function of the difference between the dispersion values of the two individual fibres. Preferably, the

15    difference between fibre dispersions is less than $12.0\text{ps}^2/\text{Km}$ and, ideally, less than $4.0\text{ps}^2/\text{Km}$. Under optiimum conditions it will be $0.1\text{ps}^2/\text{Km}$ or less. Greater differences between the two fibres results in more energy being required to form a stable pulse; we have also found that lengthening the unit cell's period (with a given pair of dispersion values) increases the required energy. The mechanism behind this increased energy

20    requirement can be understood from the intensity profile within the unit cell, figure 3. Due to the cycle of dispersive broadening and compression, the peak power of the pulse is generally lower than the initial launch power. Therefore the rate of self phase modulation (SPM) is reduced compared to the equivalent uniform fibre, and so more energy is required to balance the path-average dispersion. In the frequency domain, the process could be

25    construed as a reduction in the efficiency of four wave mixing. of which SPM is a special case.

Another highly novel feature of these solitary waves is that their pulse shapes are not the hyperbolic secants of regular optical fibre solitons. The example pulse profile which we have displayed is almost exactly Gaussian in nature, however this is only a

30    special case for that particular dispersion map. As the dispersion variation is increased there is a transition from the uniform fibre hyperbolic secant soliton (time-bandwidth-

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product 0.32) to Gaussian (0.44) form, and then to pulse shapes with higher still time-bandwidth-products. An interesting connection can be made at this point with the "stretched pulse' design of mode-locked fibre laser. These incorporate cavities with two opposite signs of dispersion and also produce Gaussian shaped pulses.

5      In cases of soliton or soliton-like transmission in dispersion compensated fibres employing a configuration with zero path average dispersion, undistorted pulse propagation was obtained in this situation due to the presence of optical filters in the recirculating loop. The stable pulses then arose from balancing SPM against filtering, rather than SPM against the path-average dispersion.

10      The technique of dispersion management has the potential to make a significant impact of the realisation of soliton communication systems. It provides major performance benefits, and has the distinct advantage of requiring only passive components. While, in a preferred embodiment, we have used equal lengths of two different fibres, alternative embodiments may use discrete dispersion compensators fabricated from highly dispersive

15   materials. The adoption of dispersion management represents a convergence between the techniques used in soliton and NRZ formatted transmission.